

Light Dark Matter, Light Higgs and the Electroweak Phase Transition

Amine Ahriche¹ and Salah Nasri²

¹*Department of Physics, University of Jijel, PB 98 Ouled Aissa, DZ-18000 Jijel, Algeria.*

²*Department of Physics, UAE University, P.O. Box 17551, Al-Ain, United Arab Emirates.*

We propose a minimal extension of the Standard Model by two real singlet fields that could provide a good candidate for light Dark Matter, and give a strong first order electroweak phase transition. As a result, there are two CP even scalars; one is lighter than ~ 70 GeV, and the other one with mass in the range $\sim 280 - 400$ GeV; and consistent with electroweak precision tests. We show that the light scalar mass can be as small as 25 GeV while still being consistent with the LEP data. The predicted dark matter scattering cross section is large enough to accommodate CoGeNT and can be probed by future XENON experiment. We also show that for dark matter mass around 2 GeV, the branching fraction of the process ($B^+ \rightarrow K^+ + 2(DM)$) can be accessible in SuperB factories.

INTRODUCTION

Understanding the nature of dark matter (DM) and the origin of the baryon asymmetry of the Universe (BAU) are two of the most important questions in both particle physics and cosmology. The Standard Model (SM) of the electroweak and strong interactions, fails in providing an explanation to these puzzles, which motivates for new physics beyond the SM. Further excitement came from the recent signal reported by CoGeNT, which favors a light dark matter (LDM) with mass in the range of $7 - 9$ GeV and nucleon scattering cross-section around $\sigma_N \sim 10^{-4}$ pb [1] (see also [2]).

With few exceptions, most of the SM extensions make no attempt to address these two puzzles within the same framework. One of the exceptions is the minimal supersymmetric standard model (MSSM) in which the neutral lightest supersymmetric particle (LSP) is a candidate for DM whereas the BAU can, in principle, be generated via the sphaleron processes when the electroweak phase transition (EWPT) is strongly first order. However, systematic studies of the effective potential show that in order to have a strongly first order EWPT, the light stop and the lightest CP even Higgs must have masses smaller than 120 GeV and 127 GeV, respectively [3]. On top of that, all the other squarks and sleptons are heavier than a few TeV, putting the original naturalness motivation under pressure. Thus, the electroweak baryogenesis in the MSSM is severely constrained. Also, the LSP with a mass around 10 GeV and an elastic scattering cross-section off a nuclei larger than $\sim 10^{-5}$ pb requires a very large $\tan\beta$ and a relatively light CP-odd Higgs. This choice of parameters leads to a sizable contribution to the branching ratios of some rare decays, which then disfavors the scenario of light neutralinos [4].

The next-to-minimal supersymmetric standard model (NMSSM), with 12 input parameters, can enhance the strength of the EWPT without the need for a light stop [5]. However, to have a LDM with an elastic scattering cross-section, that is capable to generate the CoGeNT signal, is only in a finely tuned region of the parameters

where the neutralino is mostly singlino and the light CP even Higgs is singlet-like with mass below few GeV [6]. In this case, it is very difficult to detect such a light Higgs at the LHC. On the other hand, if the lightest Higgs is SM-like, it was shown that the NMSSM is incompatible with the CoGeNT data [7].

In this work, we propose a simple and conservative extension of the SM with two real singlet scalar fields that possess a dark matter candidate lighter than 20 GeV and a strongly first order EWPT. In addition, it has the following interesting features:

- 1) There is a parameter space that can accommodate the CoGeNT signal.
- 2) The DM masses in the range of $5 \sim 9$ GeV, have a relatively large DM elastic scattering cross-section, which makes them within the reach of near future direct detection experiments.
- 3) The light CP even scalar has mass in the range of $20 \sim 70$ GeV, and still consistent with the LEP data. Whereas the heavy one has mass in the range of $280 \sim 400$ GeV, while compatible with the electroweak precision tests.
- 4) For DM mass in the range of 1.8 to 2.1 GeV, the predicted decay rate of $B^+ \rightarrow K^+ + 2(DM)$ is greater than the SM background, and can be accessible to Super B-factories.

THE MODEL

We extend the SM by adding two real, spinless and \mathbb{Z}_2 -symmetric fields: the dark matter field S_0 for which the \mathbb{Z}_2 symmetry is unbroken and another scalar field χ_1 for which its \mathbb{Z}_2 symmetry is spontaneously broken. Both fields are SM gauge singlets and hence can interact with ‘visible’ particles only via the Higgs doublet H . The tree-level scalar potential that respects \mathbb{Z}_2 -symmetries is given by [8]

$$V = -\mu^2 |H|^2 + \frac{\lambda}{6} (|H|^2)^2 + \frac{\tilde{m}_0^2}{2} S_0^2 - \frac{\mu_1^2}{2} \chi_1^2 + \frac{\eta_0}{24} S_0^4$$

$$+ \frac{\eta_1}{24} \chi_1^4 + \frac{\lambda_0}{2} S_0^2 |H|^2 + \frac{\lambda_1}{2} \chi_1^2 |H|^2 + \frac{\eta_{01}}{4} S_0^2 \chi_1^2. \quad (1)$$

The spontaneous breaking of the electroweak and \mathbb{Z}_2 symmetries introduces the two vacuum expectation values v and v_1 respectively¹. With the value of v being fixed experimentally to 246 GeV, the model will have eight independent parameters. However, the DM self-coupling constant η_0 does not enter the calculations of the lowest-order processes of this work, so effectively, we are left with seven input parameters. The minimization condition of the one-loop effective potential allows one to eliminate μ^2 and μ_1^2 in favor of (v, v_1) . The physical CP even scalars (h_1, h_2) with eigenmasses (m_1, m_2) , are related to the excitations of the neutral component of the SM Higgs doublet field, $\tilde{h} = \sqrt{2} \text{Re}(H^{(0)}) - v$, and the field $\tilde{\chi}_1 = \chi_1 - v_1$; through the mixing angle θ . In our analysis we require that (i) all the dimensionless quartic couplings to be $\ll 4\pi$ for the theory remains perturbative, (ii) and chosen in such a way that the ground state stability is insured, and (iii) the DM mass to be lighter than 20 GeV.

FIRST ORDER PHASE TRANSITION

In order to investigate the nature of the EWPT, we calculate the one-loop corrections to the tree-level potential coming from the loops of the top quark, the gauge fields, the Higgs doublet, the Goldstone bosons, and the extra singlet scalars. The one-loop effective potential at zero temperature is given in the \overline{DR} scheme by

$$V^{T=0} = V + \sum_i \frac{n_i m_i^4(\tilde{h}, \tilde{\chi}_1)}{64\pi^2} \left(\log \frac{m_i^2(\tilde{h}, \tilde{\chi}_1)}{\Lambda^2} - \frac{3}{2} \right), \quad (2)$$

where Λ is a renormalization scale which we take to be at the top quark mass, $m_i^2(\tilde{h}, \tilde{\chi}_1)$ are the field dependent squared masses, and n_i are the fields multiplicities: $n_W = 6$, $n_Z = 3$, $n_{h_1} = n_{h_2} = n_{S_0} = 1$, $n_\chi = 3$, $n_t = -12$. The finite temperature part of the effective potential [10], including the so called Daisy diagrams [11], is given by

$$V_{eff}^{(T)} = T^4 \sum_i n_i J_{B,F} \left(m_i^2(\tilde{h}, \tilde{\chi}_1)/T^2 \right) - \frac{T}{12\pi} \sum_i n_i \times \left\{ [m_i^2(\tilde{h}, \tilde{\chi}_1) + \Pi_i(T)]^{3/2} - m_i^3(\tilde{h}, \tilde{\chi}_1) \right\}, \quad (3)$$

where $J_{B,F}(\alpha) = \int_0^\infty x^2 \log(1 \mp \exp(-\sqrt{x^2 + \alpha})) dx$, and $\Pi_i(T)$ are the thermal masses. In the Daisy contribution, the summation is only performed over the scalar and longitudinal gauge fields degrees of freedom.

¹ If this model has a conformal symmetry, nonzero vevs for the SM Higgs and S_1 can still be generated by quantum correction [9]

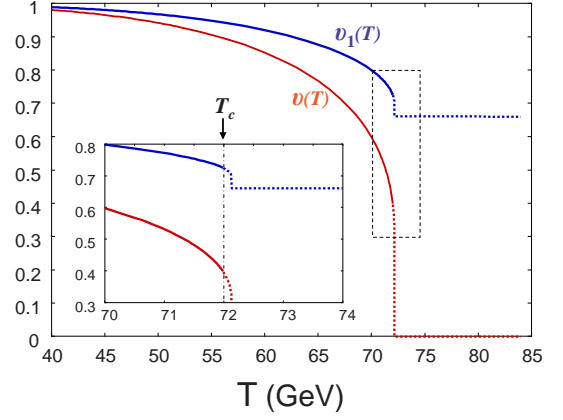


FIG. 1: The dependance of the vacuum expectation values of the doublet and singlet; $\sqrt{2} < \text{Re}(H^0(T)) >$ and $< \chi_1(T) >$, on the temperature below (solid lines) and above (dashed lines) the critical temperature.

In order to preserve the generated net baryon asymmetry from being erased by the $(B + L)$ violating sphaleron processes below the critical temperature T_c , requires that the EWPT has to be strongly first order [12]

$$v(T_c)/T_c > 1. \quad (4)$$

This criterion must hold in all extensions of the SM and in particular the ones with extra singlet fields [13].

We show in FIG. 1 the dependance of the vevs on the temperature around T_c . Unlike the SM, the position of the wrong vacuum ($0, < \chi_1(T) > \neq 0$) evolves with the temperature in such a way that the value the effective potential is shifted up with respect its value at ($0, < \chi_1(0) >$). This will result, compared to the SM, in a decrease in the critical temperature, which makes the ratio (4) larger, and therefore the EWPT stronger. In FIG. 2-a, we plot the predicted cosine square of the mixing angles that can lead to a strongly first order EWPT.

LIGHT DARK MATTER

Since S_0 is odd under the unbroken \mathbb{Z}_2 symmetry, it is a stable relic and can constitute the DM of the universe. Its relic density can be obtained using the standard approximate solution to the Boltzmann equation:

$$\Omega_D \bar{h}^2 = \frac{1.07 \times 10^9 x_f}{\sqrt{g_*} M_{Pl} \langle v_{12} \sigma_{ann} \rangle \text{ GeV}}, \quad (5)$$

where \bar{h} is the normalized Hubble constant, $M_{Pl} = 1.22 \times 10^{19}$ GeV is the Planck mass, g_* is the number of relativistic degrees of freedom at the freeze-out temperature, T_f , and $x_f = m_0/T_f$ which, for $m_0 = 1 \sim 20$ GeV, lies between 18.2 and 19.4. The quantity $\langle v_{12} \sigma_{ann} \rangle$ is the thermally averaged annihilation cross-section of S_0

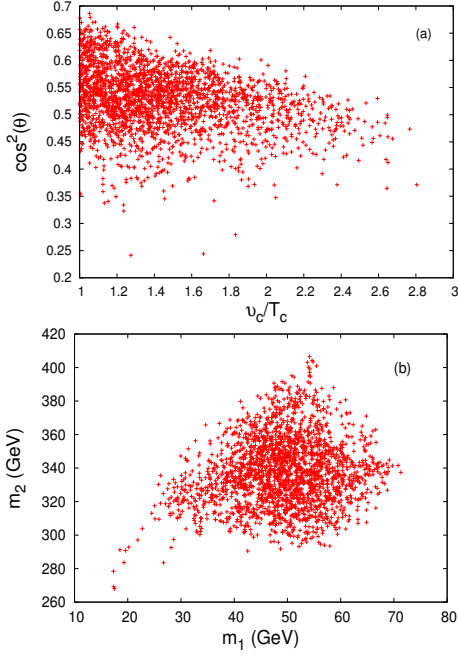


FIG. 2: The (a) $\cos^2\theta$ versus $v(T_c)/T_c$, and (b) the allowed regions of (m_1, m_2) for benchmarks that fulfill the requirements of both the DM relic density and the first order EWPT.

to light fermion pairs $f\bar{f}$, which proceeds via s-channel exchange of h_1 and h_2 for $m_f < m_0/2$ [8].

In FIG. 2-b, we present the allowed mass range for the light and the heavy Higgs for which the thermal freeze-out abundance of S_0 is in agreement with the WMAP data and also fulfill the criterion of strong EWPT. For those points, we calculate the $S_0 + \text{nucleon}$ detection cross-section using the expression

$$\sigma_{det} = \frac{(m_N - \frac{7}{9}m_B)^2 m_N^2}{4\pi v^2 (m_N + m_0)^2} \left[\frac{\lambda_0^{(3)} \cos \theta}{m_1^2} - \frac{\eta_{01}^{(3)} \sin \theta}{m_2^2} \right]^2, \quad (6)$$

where m_N and m_B are the nucleon and baryon masses in the chiral limit [14], and $\lambda_0^{(3)}$ and $\eta_{01}^{(3)}$ are the coupling constants of $h_1 S_0^2$ and $h_2 S_0^2$ given in [8]. Our predictions for the spin independent DM scattering cross-section versus the DM mass in the range $1 \sim 20$ GeV are shown in FIG. 3. We see that, beside that, it is possible to accommodate the CoGeNT signal, the elastic scattering cross-section for $m_0 = 5 \sim 8$ GeV is large enough to be probed by near-future direct detection experiments such as XENON1T [15].

We also note that in this model, the DM candidate could have masses around ~ 10 GeV, and elastic scattering cross-section with nucleon $\sim 3 \times 10^{-41} \text{cm}^2$; that is compatible with both CRESST and CoGeNT experiments. However, the overlapping region of CRESST and CoGeNT is excluded by XENON [17] when dark matter has identical couplings to protons and neutrons.

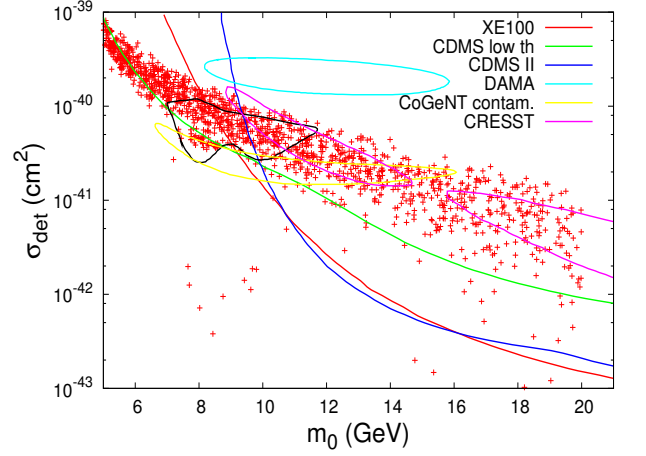


FIG. 3: The predicted S_0 direct detection cross section versus m_0 for the benchmarks presented in FIG. 2, compared to different experimental constraints such as CDMS II [16] and XENON 100 [17]. The black contour is the favored area by CoGeNT [1]. For the XENON 100 constraints, we used the lower estimate of the scintillation efficiency as described in [18]. The yellow contour is the CoGeNT allowed region with small contamination as discussed in [2], and the magenta and aqua contours represent the DAMA [19] and CRESST [20] respectively.

POSSIBLE SIGNAL AT B FACTORIES

Next, we look at the flavor changing process in which the meson B^+ decays into a K^+ plus missing energy. The corresponding SM mode is a decay into K^+ and a pair of neutrinos, with an estimated branching ratio $Br^{SM}(B^+ \rightarrow K^+ + \nu\bar{\nu}) = (3.64 \pm 0.47) \times 10^{-6}$ [21]. Since the experimental upper bound, reported by BABAR, is $Br^{Exp}(B^+ \rightarrow K^+ + Inv) < 14 \times 10^{-6}$ [22], it has been argued that (very) light DM could explain this invisible channel [23]. In our model, for $m_0 < 2.5$ GeV, the most prominent B invisible decay is into $S_0 S_0$, $\mathcal{B}_{S_0} = Br(B^+ \rightarrow K^+ + S_0 S_0)$ given by

$$\mathcal{B}_{S_0} = 6\sqrt{2} \times 10^{-5} \frac{\tau_B G_F^3 m_t^4 m_b^2 m_+^2 m_-^2}{\pi^7 m_B^3 (m_b - m_s)^2} |V_{tb} V_{ts}^*|^2 \times \int_{4m_0^2}^{m_-^2} \frac{ds}{\sqrt{s}} f_0^2(s) [(s - m_+^2)(s - m_-^2)(s - 4m_0^2)]^{\frac{1}{2}} \times \left| \frac{\lambda_0^{(3)} \cos \theta}{s - m_1^2 + im_1 \Gamma_{h_1}} - \frac{\eta_{01}^{(3)} \sin \theta}{s - m_2^2 + im_2 \Gamma_{h_2}} \right|^2. \quad (7)$$

In this relation, $\tau_B = 1.638 \pm 0.011$ ps is the B^+ lifetime, m_t , m_b and m_s are quark pole masses, $m_{\pm} = m_B \pm m_K$, V_{tb} and V_{ts} are flavor changing CKM coefficients, and $\Gamma_{h_{1,2}}$ are the decay width of the physical Higgses. The integration variable is $s = (p_B - p_K)^2 \geq 0$ where p_B and p_K are the B^+ and kaon momenta respectively. The function $f_0(s) \simeq$

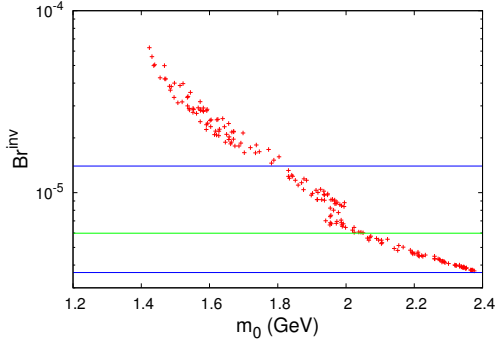


FIG. 4: The branching ratio $Br(B^+ \rightarrow K^+ + Inv)$ versus m_0 for benchmarks with the right relic density and a strong EWPT. The upper blue line represents the experimental upper bound on this rare process, while the lower one represents the expected rate according to the SM. The points above the green line have decay rate larger than the SM expectation by more than 5 times the theoretical uncertainties in $B^+ \rightarrow K^+ + \nu\bar{\nu}$.

$0.33 \exp [0.63sm_B^{-2} - 0.095s^2m_B^{-4} + 0.591s^3m_B^{-6}]$ is the form factor for $B \rightarrow K$ transition [24].

In FIG. 7, we plot the predicted range of $Br^{inv} = [B_{S_0} + Br^{SM}(B^+ \rightarrow K^+ + \nu\bar{\nu})]$ as a function of m_0 . We see that $m_0 < 1.8$ GeV are excluded, whereas masses in the range $1.80 \sim 2.38$ GeV are below the current experimental bound. It is interesting to note that for $m_0 \simeq 1.80 \sim 2.05$ GeV, the predicted branching fraction can be substantially larger than the SM expectations, and can be probed in future Super B-factories.

LIGHT HIGGS AND COLLIDER CONSTRAINTS

As we have shown above, the first order EWPT and DM constraints predict that the mass of the light CP-even scalar m_1 is in the range of $20 \sim 70$ GeV, whereas the heavy one has mass in the interval of $280 \sim 400$ GeV. Moreover, for these mass ranges are consistent with the electroweak precision tests [25].

If the recent experimental hint of a ~ 125 GeV from the LHC [26, 27] and Tevatron [28] measurements is confirmed, it implies that the electroweak phase transition in our model is not first order. Consequently, to explain the matter anti-matter asymmetry of the Universe will require invoking another mechanism for baryogenesis.

For masses lighter than ≤ 70 GeV, the LEP put strong constraints on the scale factor $k = \sigma(e^+e^- \rightarrow h_1) / \sigma^{SM}(e^+e^- \rightarrow h_1)$, which relates the production cross-section for h_1 to the SM one, and the reduction factor

$$\begin{aligned} R_{X_{SM}}(h_1) &= k \frac{Br(h_1 \rightarrow X_{SM})}{Br^{SM}(h_1 \rightarrow X_{SM})} \\ &= \frac{k^2 \Gamma_{tot}^{(SM)}(h_1)}{k \Gamma_{tot}^{(SM)}(h_1) + \Gamma(h_1 \rightarrow S_0 S_0)}. \end{aligned} \quad (8)$$

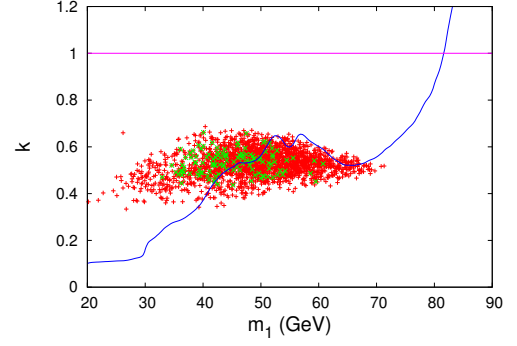


FIG. 5: The scale factor k is shown versus the lightest Higgs mass for the points that have the right dark matter relic density and a strong first order EWPT. The blue curve is the exclusion limit from OPAL [29]. The green benchmarks correspond to dark matter with masses in the range $1.8 - 2.4$ GeV presented in FIG. 4

Here, $Br^{SM}(h_1 \rightarrow X_{SM})$ is the branching fraction of the light CP even scalar decaying into any kinematically allowed SM particles, and $\Gamma_{tot}^{(SM)}(h_1)$ is its SM total decay rate. In our model, the constraints from light DM relic density and strong EWPT, result in $\Gamma(h_1 \rightarrow S_0 S_0)$ being larger than $\Gamma^{(SM)}(h_1 \rightarrow b\bar{b})$ by more than 40 times. Thus, $R_{b\bar{b}}(h_1) < 0.03 \times k^2$, which is below the LEP exclusion limit by virtue of $h_1 \rightarrow b\bar{b}$ for $m_1 < 70$ GeV.

However, OPAL collaboration provides a limit on the scale factor k from the search of neutral scalar decaying into any kinematically allowed mode, including invisible decay. In FIG. 5, we display the predicted scale factor as function of the light CP-even scalar mass. The green benchmarks correspond to the DM particles that are kinematically accessible in B^+ decay and satisfy the BABAR limit.

Similarly, the heaviest Higgs partner, produced via gluon fusion, has a reduction factor just below the ATLAS and CMS exclusion bound in the mass region of 280 GeV to 400 GeV. With 20 fb^{-1} integrated luminosity. It may still be possible for the ATLAS and CMS detectors to discover such a heavy Higgs. Clearly, this deserve a detailed study [30].

Before closing this section, we would like to mention, that if we allow the dark matter to be heavier than 20 GeV, we find it possible for the EWPT to be strongly first order with DM mass of the order $\min(m_h, m_1)/2$. Furthermore, for a Higgs mass around 125 GeV, it is possible to have $R_{\gamma\gamma}(h_{light})$ as large as 90% [30], and with heaviest Higgs partner below the CMS and ATLAS exclusion bound. The possibility of having electroweak scale DM with strongly first order EWPT was also recently realized in the inner doublet mode [31].

CONCLUSION

In conclusion, we showed that a simple extension of the SM with two real scalar fields can provide a light dark matter candidate and strongly first order phase transition. Moreover, the elastic scattering cross-sections are large enough to accommodate the CoGeNT data, and for $m_0 : 5 \sim 8$ GeV, can be tested by the future XENON experiments. Furthermore, for $m_0 \sim 2$ GeV, the predicted branching fraction of the decay of $B^+ \rightarrow K^+ + S_0 S_0$ is substantially larger than the SM background, which can be within the sensitivity of the future SuperB factories. We also found that the mass of the light CP even scalar is lying in the range 20-70 GeV without being excluded by the LEP data, whereas the heavy one has mass in the interval $280 \sim 400$ GeV, while still compatible with the ATLAS [26], and CMS [27] data. If the hint of a Higgs of mass ~ 125 GeV reported recently by the LHC and Tevatron is confirmed, then the electroweak phase transition could no longer be first order, and the BAU problem has to be explained via another mechanism.

Acknowledgement

We would like to thank J. Kopp for sharing with us the data they used to simulate the CoGeNT allowed region. This work is supported by the Algerian Ministry of Higher Education and Scientific Research under the PNR 'Particle Physics/Cosmology: the interface', and the CNEPRU Project No. D01720090023.

-
- [1] C.E. Aalseth et al., *Phys. Rev. Lett.* **107**, 141301 (2011); *Phys. Rev. Lett.* **106**, 131301 (2011).
 - [2] D. Hooper and C. Kelso, *Phys. Rev. D* **84**, 083001 (2011); C. Kelso, D. Hooper and M.R. Buckley, *Phys. Rev. D* **85**, 043515 (2012); J. Kopp, T. Schwetz and J. Zupan, *JCAP* **1203**, 001 (2012).
 - [3] M. Carena, G. Nardini, M. Quiros and C.E.M. Wagner, *Nucl. Phys. B* **812**, 243 (2009); D. Delepine, J.-M. Gerard, R.G. Felipe and J. Weyers, *Phys. Lett. B* **386**, 183-188 (1996); J.R. Espinosa, *Nucl. Phys. B* **475**, 273-292 (1996).
 - [4] V. Niro, A. Bottino, N. Fornengo and S. Scopel, *Phys. Rev. D* **80**, 095019 (2009); D. A. Vasquez, G. Belanger, C. Boehm, A. Pukhov and J. Silk, *Phys. Rev. D* **82**, 115027 (2010); E. Kuflik, A. Pierce and K.M. Zurek, *Phys. Rev. D* **81**, 111701 (2010); D. Feldman, Z. Liu and P. Nath, *Phys. Rev. D* **81**, 117701 (2010); N. Fornengo, S. Scopel and A. Bottino, *Phys. Rev. D* **83**, 015001 (2011); S. Scopel, S. Choi, N. Fornengo and A. Bottino, *Phys. Rev. D* **83**, 095016 (2011).
 - [5] K. Funakubo, S. Tao and F. Toyoda, *Prog. Theor. Phys.* **114**, 369-389 (2005); M. Pietroni, *Nucl. Phys. B* **402**, 27-45 (1993); A.T. Davies, C.D. Froggatt and R.G. Moorhouse, *Phys. Lett. B* **372**, 88-94 (1996); S.J. Huber and M.G. Schmidt, *Nucl. Phys. B* **606**, 183-230 (2001).
 - [6] P. Draper, T. Liu, C.E.M. Wagner, L.T.M. Wang and H. Zhang, *Phys. Rev. Lett.* **106**, 121805 (2011); M. Carena, N.R. Shah and C.E.M. Wagner, *Phys. Rev. D* **85**, 036003 (2012).
 - [7] J.F. Gunion, A.V. Belikov and D. Hooper, arXiv:1009.2555 [hep-ph]; D.T. Cumberbatch, D.E. Lopez-Fogliani, L. Roszkowski, R.R. de Austri and Y.L. Tsai, arXiv:1107.1604 [astro-ph.CO].
 - [8] A. Abada, S. Nasri and D. Ghaffor, *Phys. Rev. D* **83**, 095021 (2011); A. Abada and S. Nasri, *Phys. Rev. D* **83**, 075009 (2012).
 - [9] K. Ishiwata, *Phys. Lett. B* **710**, 134-138 (2012).
 - [10] L. Dolan and R. Jackiw, *Phys. Rev. D* **9**, 3320-3341 (1974); S. Weinberg, *Phys. Rev. D* **9**, 3357-3378 (1974).
 - [11] M.E. Carrington, *Phys. Rev. D* **45**, 2933-2944 (1992).
 - [12] M.E. Shaposhnikov, *Nucl. Phys. B* **287**, 757-775 (1987); *B* **299**, 797-817 (1988).
 - [13] A. Ahriche, *Phys. Rev. D* **75**, 083522 (2007); A. Ahriche and S. Nasri, *Phys. Rev. D* **83**, 045032 (2011); J. R. Espinosa, T. Konstandin and F. Riva, *Nucl. Phys. B* **854**, 592 (2012).
 - [14] X.G. He, T. Li, X.Q. Li, J. Tandean, and H.C. Tsai, *Phys. Rev. D* **79**, 023521 (2009); Y. Cai, X.G. He, and B. Ren, *Phys. Rev. D* **83**, 083524 (2011); M. Asano and R. Kitano, *Phys. Rev. D* **81**, 054506 (2010).
 - [15] Talk by E. April at the UCLA Dark Matter 2012, Tenth Symposium on Sources and Detection of Dark Matter and Dark Energy in the Universe.
 - [16] Z. Ahmed et al., *Phys. Rev. Lett.* **102**, 011301 (2009); *Science* **327**, 1619 (2010).
 - [17] E. Aprile et al., *Phys. Rev. Lett.* **105**, 131302 (2010).
 - [18] A. Manzur, A. Curioni, L. Kastens, D.N. McKinsey, K. Ni and T. Wongjirad, *Phys. Rev. C* **81**, 025808 (2010).
 - [19] R. Bernabei et al., *Eur. Phys. J. C* **67**, 39 (2010).
 - [20] G. Angloher et al., arXiv:1109.0702 [astro-ph.CO].
 - [21] M. Bartsch, M. Beylich, G. Buchalla and D.N. Gao, *JHEP* **0911**, 011 (2009).
 - [22] K.F. Chen et al., *Phys. Rev. Lett.* **99**, 221802 (2007).
 - [23] C. Bird, P. Jackson, R. Kowalewski and M. Pospelov, *Phys. Rev. Lett.* **93**, 201803, (2004).
 - [24] A. Ali, P. Ball, L.T. Handoko and G. Hiller, *Phys. Rev. D* **61**, 074024 (2000).
 - [25] V. Barger, P. Langacker, M. McCaskey, M.J. Ramsey-Musolf and G. Shaughnessy, *Phys. Rev. D* **77**, 035005 (2008); S. Baek, P. Ko and W. I. Park, *JHEP* **1202**, 047 (2012).
 - [26] G. Aad et al. [ATLAS Collaboration], *Phys. Rev. Lett.* **108**, 111802 (2012); F. Gianotti, ATLAS-CONF-2011-163.
 - [27] S. Chatrchyan et al. [CMS Collaboration], *Phys. Lett. B* **699**, 25 (2011); *Phys. Lett. B* **710**, 403 (2012); G. Tonelli, CMS-PAS-HIG-11-032-425.
 - [28] The TEVNP Working Group, for the CDF, D0 Collaborations, arXiv:1203.3774 [hep-ex].
 - [29] G. Abbiendi, et al., *Eur. Phys. J. C* **27**, 311-329, (2003).
 - [30] A. Ahriche and S. Nasri, *in preparation*.
 - [31] T.A. Chowdhury, M. Nemevsek, G. Senjanovic and Y. Zhang, *JCAP* **1202**, 029 (2012).